PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No./(Center No.) E-18-635 (R6285-0A0) GTRC/GIT DATE 3 / 30 / 87

Project Director: S.R. Stock School/Lab Material Engineering

Sponsor: National Science Foundation

Agreement No.: Grant No. MSM-8614493

Award Period: From 2/15/87 To 7/31/88* (Performance) 10/31/88 Reports

Sponsor Amount: New With This Change | Total to Date

Contract Value: $ ______ $ 29,986

Funded: $ ______ $ 29,986

Cost Sharing No./(Center No.) E-18-316 (F6285-0A0) Cost Sharing: $ 3,000

Title: High Resolution Synchrotron Computed Tomography For Engineering Applications

ADMINISTRATIVE DATA

OCA Contact John B. Schonk x4-4820

1) Sponsor Technical Contact:

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Washington, DC 20550

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Military Security Classification: ______

(or) Company/Industrial Proprietary: ______

ONR Resident Rep. is ACO: ______ Yes ______ No

Defense Priority Rating: ______

RESTRICTIONS

See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:

*Includes 6 month unfunded flexibility period

No funds may be expended after 7/31/88

COPIES TO:

SPONSOR'S I.D. NO. ______

Project Director
Research Administrative Network
Research Property Management
Accounting

Procurement/GTRI Supply Services
Research Security Services
[redacted]
Research Communications

GTRC
Library
Project File
Other

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Date 3/6/89

Project No. E-18-635 Center No. R6285-0A0

Project Director S. R. Stock School/Lab Mat. Eng.

Sponsor National Science Foundation

Contract/Grant No. MSM-8614493 GTRC XX GIT ____

Prime Contract No. ____

Title High Resolution Synchrotron Computed Tomography for Enginnering Applications

Effective Completion Date 10/31/88 (Performance) 1/31/89 (Reports)

Closeout Actions Required:

- X None
- ___ Final Invoice or Copy of Last Invoice
- ___ Final Report of Inventions and/or Subcontracts
- ___ Government Property Inventory & Related Certificate
- ___ Classified Material Certificate
- ___ Release and Assignment
- ___ Other ____

Includes Subproject No(s). ____

Subproject Under Main Project No. ____

Continues Project No. ____ Continued by Project No. ____

Distribution:

- X Project Director
- X Administrative Network
- X Accounting
- X Procurement/GTRI Supply Services
- X Research Property Management
- ___ Research Security Services
- [redacted]
- X GTRC
- X Project File
- X Contract Support Division (OCA)
- ___ Other ____

E 18-625

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550	FINAL PROJECT REPORT NSF FORM 98A	
PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING		
PART I—PROJECT IDENTIFICATION INFORMATION		
1. Institution and Address Georgia Tech Research Corporation Georgia Institute of Technology Atlanta, GA 30332-0420	2. NSF Program ENG/MSM	3. NSF Award Number MSM - 8614493
	4. Award Period From 2/19/87 To 10/31/88	5. Cumulative Award Amount $29,986
6. Project Title High Resolution Synchrotron Computed Tomography for Engineering Applications		

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

Computed tomography, developed for medical diagnostic procedures, is being used increasingly for non-destructive evaluation of structural components. This project is centered on the development of high resolution tomography, or microtomography, for these engineering applications. Processing-related porosity in silicon carbide/silicon nitride composites and damage in silicon carbide/aluminum composites were studied with microtomography. The spatial distribution of porosity in the ceramic-matrix composite was revealed clearly as was microcracking in the metal-matrix composite. The visibility of cracks was also studied in the metal-matrix composite material. The results indicate that microtomography can and will play an important role in uncovering fundamental mechanisms of damage accumulation and of processing-related defect inclusion in advanced engineering materials.

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	TO BE FURNISHED SEPARATELY TO PROGRAM: Approx. Date
a. Abstracts of Theses	X				
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other *(specify)* i. presentations at national/international meetings. ii.) proposals resulting from program's accomplishments		X X			

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Stuart R. Stock		Feb 17, 1989

PART IV - SUMMARY DATA ON PROJECT PERSONNEL

NSF Division ENG/MSM

The data requested below will be used to develop a statistical profile on the personnel supported through NSF grants. The information on this part is solicited under the authority of the National Science Foundation Act of 1950, as amended. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. NSF requires that a single copy of this part be submitted with each Final Project Report (NSF Form 98A); however, submission of the requested information is not mandatory and is not a precondition of future awards. If you do not wish to submit this information, please check this box ☐

Please enter the numbers of individuals supported under this NSF grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

*U.S. Citizens/ Permanent Visa	PI's/PD's		Post-doctorals		Graduate Students		Under-graduates		Precollege Teachers		Others	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
American Indian or Alaskan Native	0	0	0	0	0	0	0	0	0	0	0	0
Asian or Pacific Islander	0	0	0	0	0	0	0	0	0	0	0	0
Black, Not of Hispanic Origin	0	0	0	0	0	0	0	0	0	0	0	0
Hispanic	0	0	0	0	0	0	0	0	0	0	0	0
White, Not of Hispanic Origin	1	0	0	0	0	0	0	0	0	0	0	0
Total U.S. Citizens	1	0	0	0	0	0	0	0	0	0	0	0
Non U.S. Citizens	0	0	0	0	1	0	0	0	0	0	0	0
Total U.S. & Non-U.S. ..	0	0	0	0	1	0	0	0	0	0	0	0
Number of individuals who have a handicap that limits a major life activity.	0	0	0	0	0	0	0	0	0	0	0	0

*Use the category that best describes person's ethnic/racial status. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN OR PACIFIC ISLANDER: A person having origins in any of the original peoples of the Far East, Southeast Asia, the Indian subcontinent, or the Pacific Islands. This area includes, for example, China, India, Japan, Korea, the Philippine Islands and Samoa.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa or the Middle East.

THIS PART WILL BE PHYSICALLY SEPARATED FROM THE FINAL PROJECT REPORT AND USED AS A COMPUTER SOURCE DOCUMENT. DO NOT DUPLICATE IT ON THE REVERSE OF ANY OTHER PART OF THE FINAL REPORT.

PART III

b. <u>Publication Citations</u>

1. "Microtomography of Silicon Nitride/Silicon Carbide Composites," S. R. Stock, A. Guvenilir, T. L. Starr, J. C. Elliott, P. Anderson. S. D. Dover and D. K. Bowen, accepted for <u>Advanced Techniques for Characterization of Ceramics</u> (Am. Cer. Soc./MRS. 1989).

2. "Synchrotron Microtomography of Composites," S. R. Stock, J. H. Kinney, T. M. Breunig, U. Bonse, S. D. Antolovich, Q. C. Johnson and M. C. Nichols, accepted for <u>Synchrotron Radiation in Materials Research</u> (MRS, 1989).

<u>Anticipated Publications, Journal (if known) and Submission Dates</u>

1. "Detectability of Cracks in Continuous-Fiber, Metal Matrix Composites Using Microtomography," T. M. Breunig, S. R. Stock, J. C. Elliott. A. Guvenilir, S. D. Antolovich, P. Anderson, S. D. Dover and D. K. Bowen, est. June 1989.

2. "Processing Induced Porosity and Density Variation in Silicon Carbide/Silicon Nitride Ceramic Matrix Composites," A. Guvenilir, S. R. Stock, J. C. Elliott, T. L. Starr, P. Anderson. S. D. Dover and D. K. Bowen, Phil Mag A, J. Am. Cer. Soc. or J. Mat. Res., est. June 1989.

c. <u>Data on Scientific Collaborators</u>

The investigations described in this part were primarily the work of the principal investigator and the research assistant indicated with an asterisk. The Georgia Tech personnel who participated in various aspects of the study partially supported by this project are listed below.

The tomography experiments were carried out in collaboration with two research groups, both of which involve multiple institutions, listed below. Collaborative work is continuing.

<u>Georgia Institute of Technology</u>

*Mr. A. Guvenilir (Materials Engineering)
Mr. T. M. Breunig (Materials Engineering)
Dr. T. L. Starr (GTRI)
Dr. S. D. Antolovich (Materials Engineering)

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Lawrence Livermore National Laboratory

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Exploratory Chemistry Division
Sandia National Laboratory
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Professor U. Bonse, et al.
University of Dortmund
Dortmund, FRG

e. Technical Description of Project and Results

1. Introduction

The initial goal of this project was to develop a high resolution computed tomography (CT) facility at the X-14 line of the National Synchrotron Light Sources (NSLS). The pinhole approach, described below, was to be used for high resolution CT or microtomography. Computer routines for data collection and analysis were to be developed.

The original plan was abandoned when it was apparent that much greater impact could be achieved by aggressively pursuing an alternative plan of research, and there were two principal reasons for this change. First was the lengthy shutdown of NSLS. While the programming side would not be hindered, too little experimental time would be available. Second, soon after the project was awarded, the EXXON and Lawrence Livermore microtomography groups announced their success with parallel data collection schemes (also described below). It was natural for this project to use their experience in collaborative experiments. The instrumentation development we originally proposed was only the first step in exploiting microtomography for engineering applications, and by developing collaboration we were able to progress much farther in assessing the impact of microtomography in engineering applications.

The research conducted centered on collaborative microtomography experiments with the London Hospital Medical College group (LHMC) headed by Dr. J. C. Elliott and with the Lawrence Livermore group (LLNL) headed by Dr. J. H. Kinney. The former group uses a relatively simple apparatus and pinhole collimation, and the collaborative experiments employed radiation from a laboratory microfocus source. The LHMC group is also constructing a new model of their apparatus for our laboratory, so that collaborative experiments may be continued at both locations. Our collaborative work with the LLNL group used parallel data collection and synchrotron radiation.

Six areas of potential impact of microtomography were identified in the proposal: a) delamination in polymeric composites, b) grain boundary cavitation during high temperature creep and fatigue, c) cracking below metal contacts in semiconductor substrates, d) fracture and bone ingrowth in porous biomedical materials, e) impurities in coal and f) processing-induced porosity in ceramic matrix composites. In a project of this scope, it is clearly impossible to study all of the areas. Areas a) and d) involve much larger specimens than we can accommodate at present, and their study was postponed. Area e) has been investigated by the LLNL group, and we saw no need to duplicate their efforts. No interesting specimens were obtained for investigation in area c), so that effort concentrated on b) and f) and on damage in metal matrix composites, an unanticipated area of research. Unfortunately the synchrotron beam time for tomography of Cu-Sb samples with grain boundary cavities was lost due to the beam problems; this characterization has been scheduled for February 1989.

Attention was focused on processing defects and mechanically-induced damage in advanced composite materials. Specifics of the techniques used are discussed in Section 2, Background. Results of research supported under this project are presented and briefly discussed in Section 3. Scientific and Technological impact is discussed in Section 4 and Recommendations in Section 5.

2. Background

In computed tomography and high resolution variants termed microtomography, the spatial variation of x-ray absorption in a thin slice or cross-section of the sample is recorded for various projection directions or views, the number of which depend on the ultimate resolution desired [1]. The different views are combined via a reconstruction algorithm, and the two dimensional map of x-ray absorption across the slice is obtained [2,3]. The three-dimensional distribution of absorption in the sample is recovered by stacking successive slices. This approach is much superior to microradiography where features of interest can be obscured if the sample is too thick or if there are too many overlapping features. Cracks and their precursors are much more readily detected with computed tomography because geometric invisibility is no longer possible: a crack produces virtually no contrast except when viewed from directions near its plane.

Spatial resolution has always been a limitation of tomography apparatus. Medical units have resolution approaching 0.5 mm in most cases, although a specialized industrial unit with 50 μm resolution has been described for samples with dimensions on the order of inches [4,5]. Systems using ribbon-like x-ray beams (from rotating anode sources) and multiple detector arrays are limited to spatial resolution no better than 25 μm because of the intrinsic dimness of conventional x-ray sources.

Elliott and Dover [6] used the translate-rotate scheme (the specimen is translated across the narrow beam to obtain each absorption profile, and then it is rotated for the next view), a microfocus x-ray generator and a 15 μm diameter collimator to obtain very high resolution microtomographs of human femoral bone. Their apparatus is shown schematically in Fig. 1. Counting time per slice was about 19 h for a 0.8 x 0.8 mm^2 sample (128 points, each counted for 10 s, per projection and 54 projections at 3 1/3° intervals per slice), and undersampling (~130 projections should have been recorded) blurred the image.

Data acquisition rates can be improved with the LHMC scanner if synchrotron radiation is used. Synchrotron radiation is produced when electrons traveling at relativistic velocities are deflected by the bending magnets, wigglers or undulators of a storage ring. The brightness of synchrotron <u>white</u> radiation is at least two orders of magnitude higher than that of <u>characteristic</u> peaks from the most powerful laboratory sources [7]. The broad spectrum of synchrotron radiation allows selection via monochromators of the most appropriate wavelengths for a given specimen; one is not limited to wavelengths of characteristic lines. Spatially-broad and well-collimated beams are natural property of synchrotron radiation and provide a considerable advantage over conventional x-ray sources. Bowen, Elliott, Stock and Dover [8] used the LHMC apparatus and synchrotron radiation to study human femur bone and sintered alumina with 4 and 10 μm diameter collimators, respectively. Counting times were 1 s/position (128 positions/profile) for the 2 mm square alumina specimen, and 64 views of the sample were recorded in about 4 h.

The LLNL and EXXON groups have chosen to use parallel data collection. The LLNL group uses a fluorescent screen coupled through a lens to a CCD (charge coupled device) array and have obtained spatial resolution of about 5 μm at the Stanford Synchrotron Radiation Laboratory (SSRL) and at the German Electron Synchrotron Source (DESY) [1]. A schematic of their apparatus is shown in Fig. 2. Many absorption profiles are recorded simultaneously so that the data collection rate is orders of magnitude faster.

The advanced composites which are studied were random fiber SiC/Si_3N_4 CMC and continuous fiber SiC/Aℓ MMC. The SiC fibers were 15 and 142 μm in diameter for the CMC and MMC materials, respectively. The CMC was studied to establish sensitivity of microtomography to processing defects, and the MMC was studied to define damage/crack detectability limits for different levels of spatial resolution.

The addition of SiC or other dispersoids (particles, whiskers or fibers) to silicon nitride matrices offers a potential for considerable improvement of fracture toughness and strength [9]. Apparently, the strong ceramic fibers can prevent catastrophic brittle failure by providing extra energy dissipation during crack advance [10]. The silicon nitride matrix/silicon carbide fiber system has received considerable attention [10-14] particularly since commercial, continuous-polymer derived SiC fibers such as Nicalon provide good chemical compatibility and degradation resistance superior to carbon fibers in high temperature oxidizing environments. Complete densification of sintered or chemical vapor infiltrated (CVI) specimens is frequently impossible, however, due to the formation of stable pores in the interior of grains or to the enclosure of pores by growth of the matrix on surrounding fibers. The resulting lower density and large number of internal stress concentrators leads to poor mechanical properties. If the porosity cannot be eliminated during processing, most of the anticipated fracture toughness will be lost.

Continuous fiber reinforced SiC/Al MMC are designed for higher temperature structural applications in the aerospace industry. Composites similar to these (but as yet undefined) are envisioned for application in the National Aerospace Plane (NASP), the Advanced Tactical Fighter (ATP), manned space stations, etc. A major effect on the mechanical properties of MMC's is the damage induced by thermal cycling. As the structure undergoes a thermal cycle, the coefficient of thermal expansion mismatch between fiber and matrix initiates fatigue damage and debonding at the fiber/matrix interface. The damage is very difficult to detect experimentally because of crack closure when the externally applied loads are removed. The current methods for assessing the damage state are based upon stiffness loss [15-17]. They do not, however, provide an adequate indication of the location and quantity of damage present. Knowledge of the crack initiation and propagation stages, a measure of the total quantity of damage present and a descriptive model for damage evolution are required for prediction of the remaining life of a structure.

3. Results Obtained

The London Hospital Medical College (LHMC) apparatus was used with laboratory microfocus radiation to study porosity as a function of processing conditions in SiC/Si_3N_4. We recorded a large number of adjacent slices with a 10 μm diameter collimator, and differences in porosity were clearly evident. The sample shown in Fig. 3 and 4 was produced by reaction bonding, was approximately 1 mm^2 in cross-sectional area and contained considerable porosity. Each pixel in the reconstructed images is about 20 to 10 μm on a side in Fig. 3 and 4, respectively. The higher resolution in Fig. 4 is due to the larger number of views recorded for these slices. The lighter areas represent regions of low x-ray absorption, and the slices are reproduced with 256 gray levels. Adjacent slices (numbered) are separated by 20 μm, large trapped pores and highly densified volumes are clearly visible, but individual 15 μm fibers are not resolved in these tomographs. Tomographs were also recorded from a second Si_3N_4/SiC composite which had been processed to eliminate the porosity. As expected, these tomographs revealed little porosity with dimensions greater than 10 μm.

One key element in the analysis is the resolution of individual fibers whose x-ray absorption is quite similar to the matrix and whose 15 μm diameter is only slightly larger than the ~10 μm pixel size. The random orientation of the fibers necessitates three dimensional presentation of the adjacent slices; limited ranges of absorption will be mapped so that the resulting skeletal image will emphasize connected porosity or fibers. The data also allows determination of the average density of the sample; when this part of the analysis is complete, this density can be compared with that determined by macroscopic techniques. The distribution of pore sizes is also currently under investigation. A paper for submission to an archival journal (such as Philosophical Magazine A, Journal of Materials Research or Journal of the American Ceramics Society) will follow the completion of the analysis.

Damage in a continuous fiber SiC/Al MMC has also been studied with the LHMC apparatus; the sample was split parallel to and between the unidirectional fibers by a wedge [10]. The resulting crack stayed between plies of fibers for the most part, although SEM micrographs of the side of the sample revealed some micro-cracking and fiber breakage. The wedge was left embedded in the sample so that a gradient of crack openings and their visibility could be studied with microtomography (Fig. 5). Resolution was quite poor due to the fact that the wedge required a large sample to collimator separation; the limit of crack detectability cannot, therefore, be determined from this data. We can, however, determine the minimum crack opening displacement which produced significant contrast for this particular pixel size. The volume fraction of crack within the pixel can be estimated from the observed contrast and can be correlated with an extrapolation of crack openings measured at different distances from the wedge. When complete, this work will also be published in the open literature.

Figure 6 shows a slice (normal to the fibers) recorded during synchrotron microtomography of the SiC/Al MMC [20]. The sample was deformed in three point bending, and what appears to be a cracked fiber is indicated by the red image in the interior of the slice. The results were obtained at DESY in collaboration with the Lawrence Livermore microtomography group, headed by Dr. J. H. Kinney, and with the University of Dortmund group, headed by Professor U. Bonse. Over 100 slices of each sample were recorded simultaneously using the CCD detector. The data was collected with 25 keV radiation, the width of the slice was about 12 μm, and the pixel size was about the same. Only 60 views were recorded, and the undersampling caused the graininess in the image. Note that no image enhancement has yet been applied to this data, and ring artifacts are present. Refinement of the reconstruction, presently underway, will suppress this artifact. Sequential viewing of a series of slices on a high resolution image terminal reveals clearly the bending of the sample (displacement of the image), displacement of intact fibers from their positions in the undamaged composite and fracture of fibers. The series of slices also showed that ends of the fractured fibers separated and that matrix material flowed into and filled the resulting cavity. Figures 7 and 8 show three-dimensional representations of the slices: the former shows different "sectioning" planes and the latter shows only the carbon cores. This type of data presentation is extremely effective for damage studies.

4. Scientific and Technological Impact

The power of microtomography for processing defect characterization and for damage determination in MMC and CMC has been demonstrated. This study has shown the tomography can lead to improved understanding of damage and of processing-related defects in composites. This is a prerequisite for improved life-prediction and process modeling, for wider use of composites and for extensive economic impact of this strategy for obtaining enhanced properties. Better understanding of damage mechanisms and their relationship to processing defects will be the first step to a new generation of high performance composites. Studying the same specimen multiple times during the processing cycle or the deformation test allows the clearest identification of the mechanisms controlling macroscopic properties. Sample-to-sample variability, which often plagues composite studies, can not be eliminated.

Higher resolution must be obtained, and better means for presenting the three-dimensional data must be devised. Correlation of tomographic images with well-understood and accepted techniques such as fractography are necessary for the confident interpretation of results. Development of this type of database on relatively complex materials such as composites will lay the groundwork for widespread, routine NDE of composites and of monolithic materials with these techniques. Achievement of 1 μm resolution over millimeter-wide dimensions will fill the gap between electron microscopy and statistical sampling techniques such as small angle scattering on the one hand and macroscopic measuring techniques on the other. The previously inaccessible size range is where microscopic mechanisms link with macroscopic behavior (and associated continuum models), and, as such, its study is critical for physically based modeling.

5. Recommendations

This relatively small research effort has demonstrated the huge impact that microtomography can have on the understanding of fundamental mechanisms in engineering applications. The approach of collaboration with groups working primarily on instrumentation has been synergistic, and the scientific and technological benefits of the funds expended for this program are exceptionally high.

Progress in the fundamental understanding of damage accumulation in CMC, PMC and MMC appears very likely if microtomography is developed further. Advances in the technique's sensitivity and spatial resolution must also be a goal. Increasing the volume of material which can be studied with microtomography is critical if it is to be used with specimens for which fracture mechanics calculations are valid (e.g. 1 cm^2 cross-sections instead of the 2 mm^2 which are presently feasible). Resolution of 1 μm and contrast better than 4% are goals which can be met in the next few years. The examination of larger diameter samples will also be possible, and it is not too optimistic to envision microtomography studies of samples with 5 mm or greater diameters. Another issue central to NDE of structural composites and to understanding basic failure mechanisms is the role of the loading state in the detectability of cracks. It is essential to know whether complex loading stages will be needed for routine NDE imaging. If damage is hidden by the removal of loads (if cracks or fiber-breaks close when the imposed strain is released), the amount of "invisible" damage or its fractions of the total damage should be established. Finally, the relationship of damage accumulation to processing flaws or to fiber arrangement must be determined.

Effort should concentrate, therefore, on the fundamental aspects of damage initiation and accumulation, on the link between microscopic features and macroscopic mechanical behavior of composites and on microstructure-based modeling of phenomena such as stiffness loss. The understaning developed will be a key to improved composite design and processing, and industrial interactions will be essential in assuring improvements in the next generation of composite materials. Making use of and refining instrumentation advances made elsewhere. promises exceptional scientific and technological advances for a very modest level of effort. Interpretation of data will be much clearer because the sample samples can be examined many times during the course of the deformation test. This approach of microtomographic damage characterization will therefore, provide exciting, and perhaps unprecedented, advances in understanding damage initiation and accumulation.

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18. S. R. Stock, A. Guvenilir, T. L. Starr, J. C. Elliott, P. Anderson, S. D. Dover and D. K. Bowen in: Advanced Characterization Techniques for Ceramics (in press).

19. T. M. Breunig, S. R. Stock. A. Guvenilir, J. C. Elliott, P. Anderson, S. D. Dover, D.d K. Bowen and S. D. Antolovich, unpublished data.

20. S. R. Stock, J. H. Kinney, T. M. Breunig, U. Bonse, S. D. Antolovich, Q. C. Johnson and M. C. Nichols, in: Synchrotron Radiation in Materials Research (in press).

f. Presentations at National and International Meetings

1. "Microtomography of Silicon Nitride/Silicon Carbide Composites," S. R. Stock, et al., at TMS-AIME, 1988 Fall Meeting, Chicago, Illinois, September 29, 1988.

2. "Microtomography of Silicon Nitride/Silicon Carbide Composites," S. R. Stock, et al., at Symposium on Advanced Characterization Techniques for Ceramics (Am. Cer. Soc./MRS), San Francisco, California, October 24, 1988.

3. "Application of Microtomography to the Study of Ceramic and Metal Matrix Composites, S. R. Stock, at Symposium on Thermal and Mechanical Behavior of Ceramic and Metal Matrix Composites (ASTM), Atlanta, Georgia, November 8, 1988.

4. "Application of Microtomography of Composites," S. R. Stock, et al., at Symposium V: Synchrotron Radiation in Materials Research (MRS), Boston, Massachusetts, November 30, 1988.

5. "Microtomography of Damage in SiC/Aℓ Continuous Fiber Composites," T. M. Breunig, S. R. Stock, et al., at TMS-AIME 1989 Annual Meeting, Las Vegas, Nevada, February 28, 1989.

Proposals Resulting from Program Accomplishments

1. "US-UK Cooperative Research - Novel X-ray Methods for Characterization of the Spatial Distribution of Inhomogeneities in Materials," NSF grant INT-8814774, $15,067, 11/1/88-4/30/92.

2. "US-France Cooperative Research: Characterization of Damage in Composites by Microradiography, Computed Tomography and Microtomography," NSF proposal INT-8815501, not funded.

3. "Computed Tomography Apparatus for Evaluation of Consolidation during Processing of Monolithic and Composite Ceramics," E. J. Grassmann Trust, $20,000, July 1988.

4. "A Study of the Relationship between Macroscopic Measures and Physical Processes Occurring during Crack Closure," ONR, January 1989, $303,107, pending.

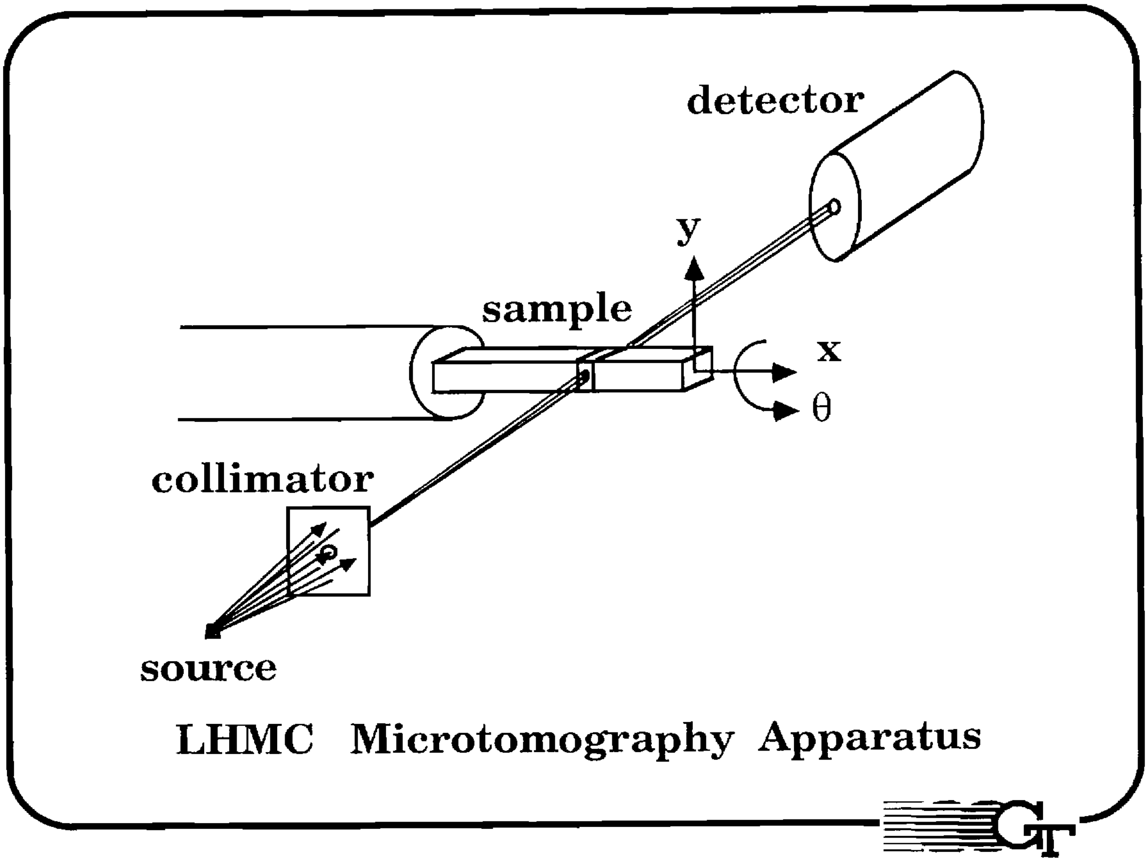

Figure 1. Schematic of the London Hospital Medical College pinhole microtomography apparatus.

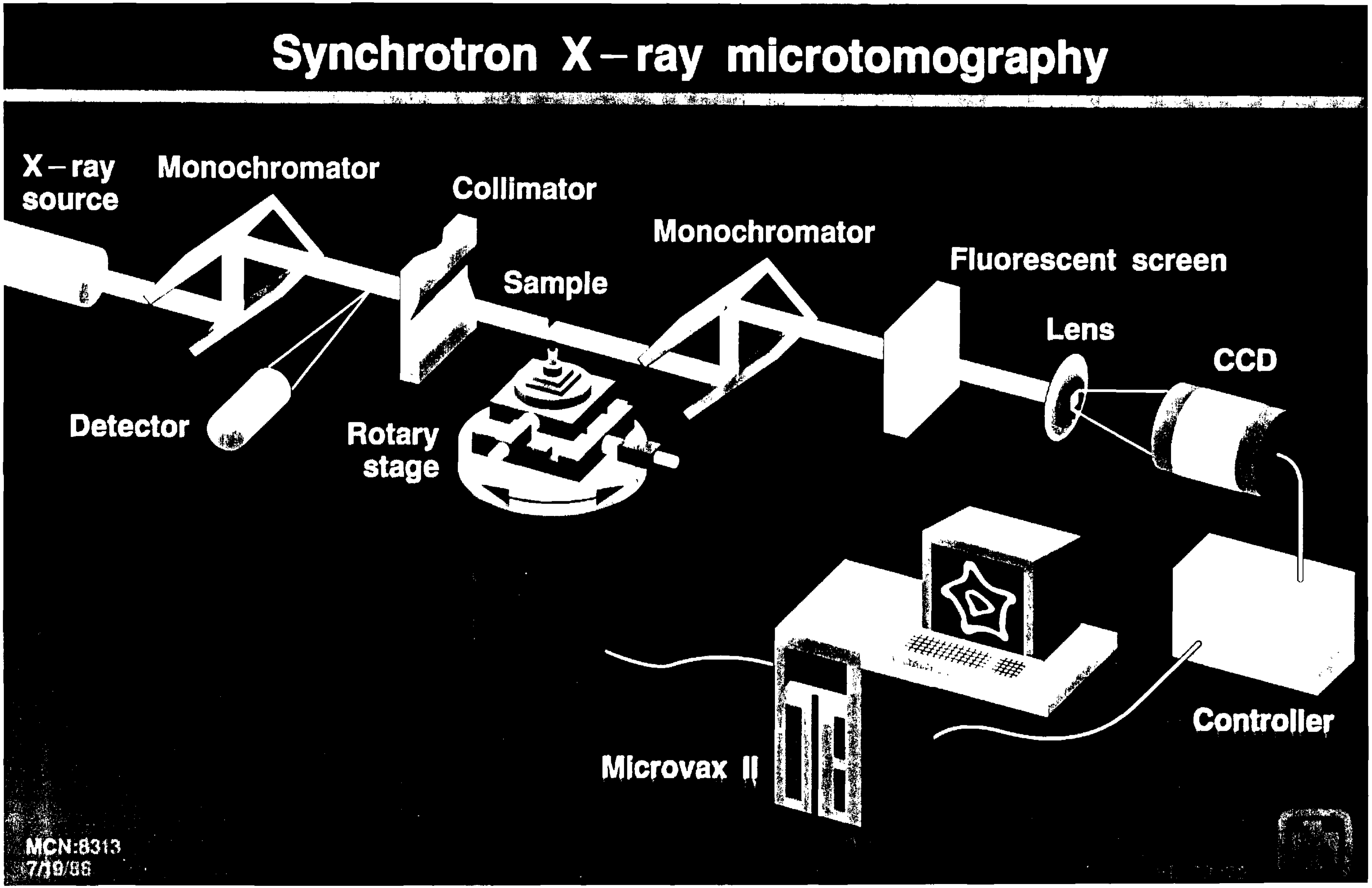

Figure 2. Schematic of the Lawrence Livermore National Laboratory CCD-based microtomography apparatus.

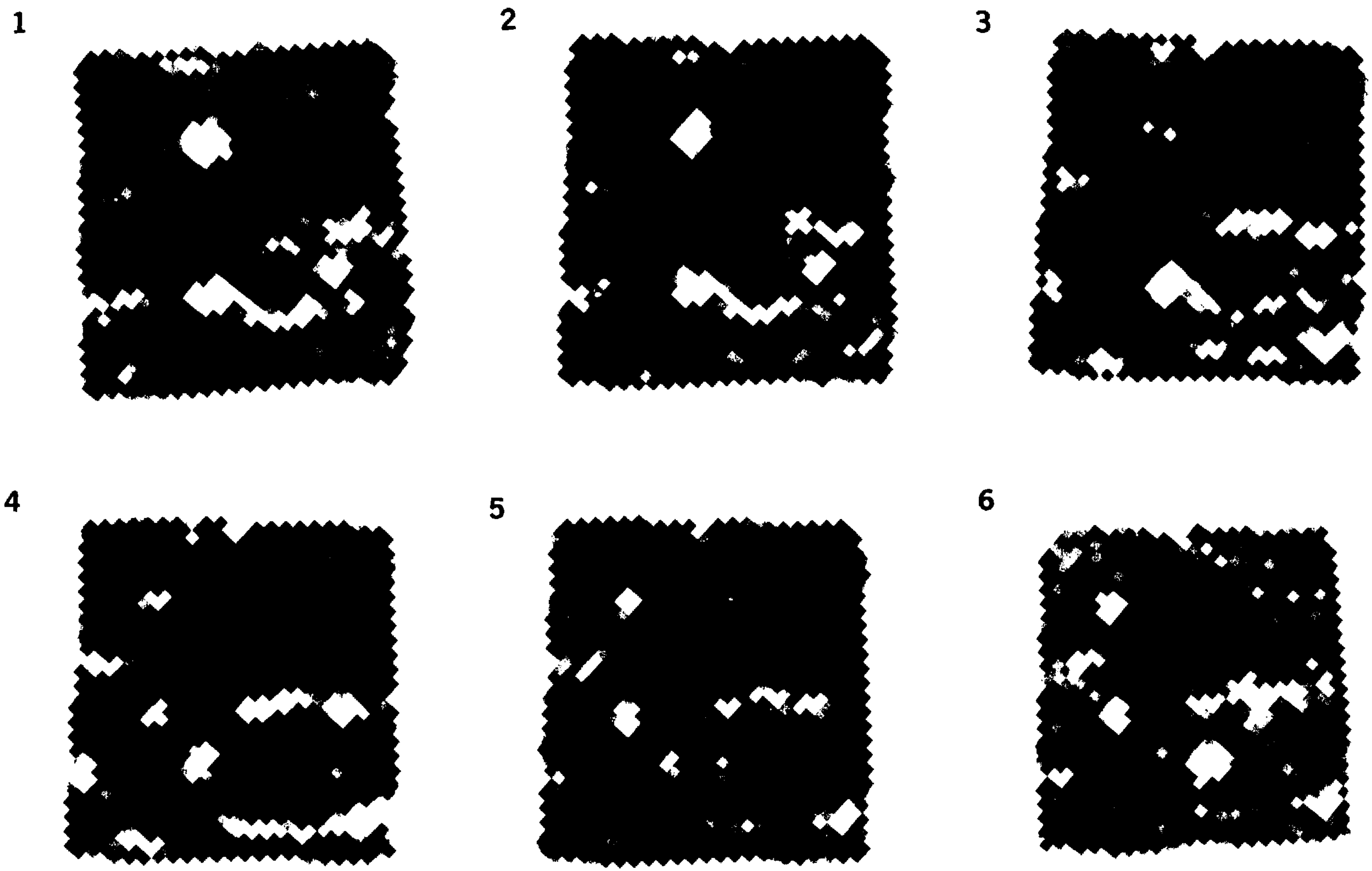

Figure 3. Silicon nitride/silicon carbide composite (1 mm^2 cross-section)
Sample N-1-4 (porous) Reconstructions SIL
10 um dia. collimator, 20 um between slices, 3 deg/ view
Darker pixels have higher x-ray absorption.

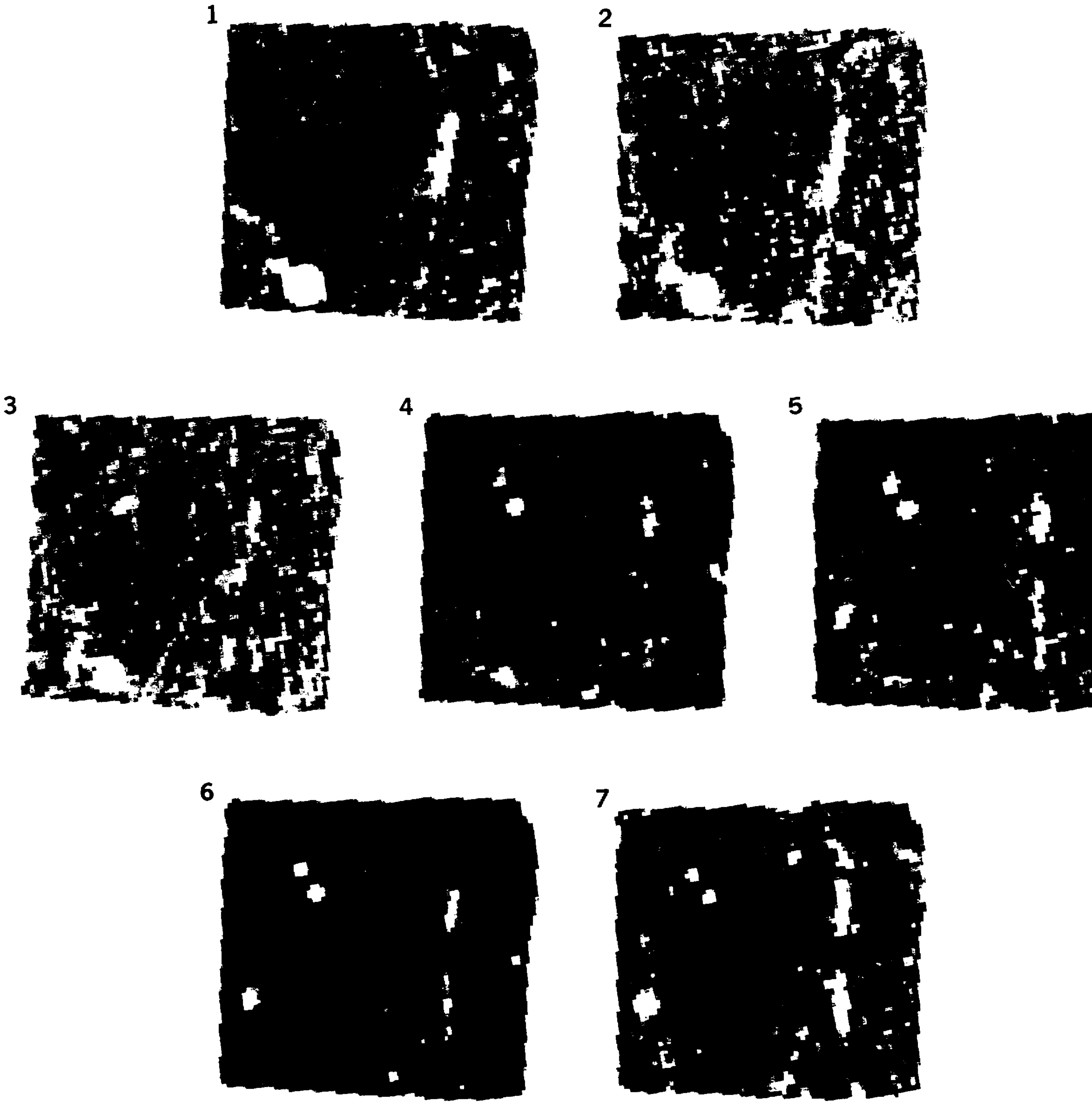

Figure 4.

Silicon nitride/silicon carbide composite (1 mm2 cross-section)
Sample N-1-4 (porous) Reconstructions SIL3
10 um dia. collimator, 10 um between slices, 1.5 deg/ view
Darker pixels have higher x-ray absorption.

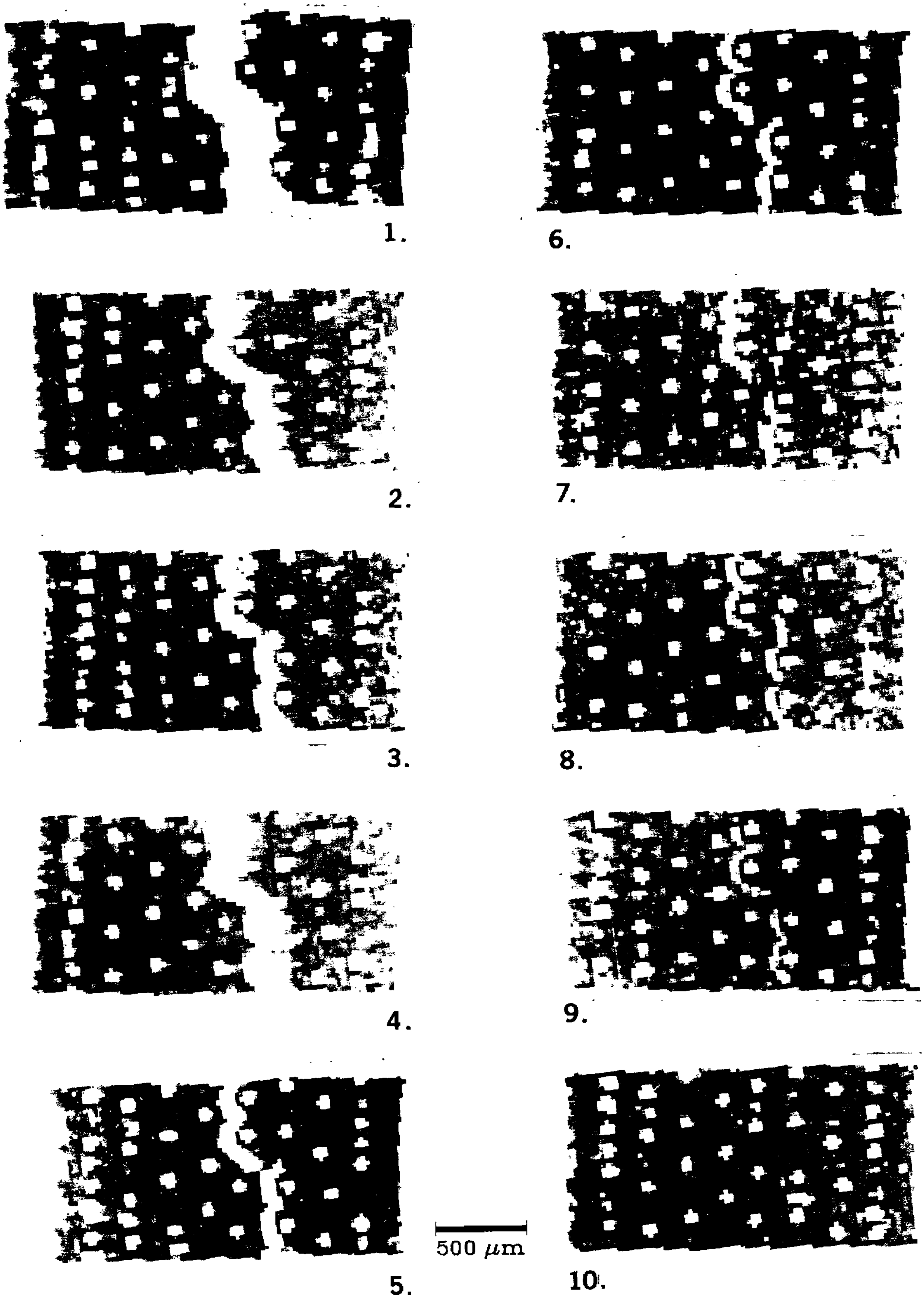

Figure 5. Slices perpendicular to a crack in a SiC/Al MMC, illustrating the variation in crack opening with distance from the wedge. The lower numbers are closer to the wedge.

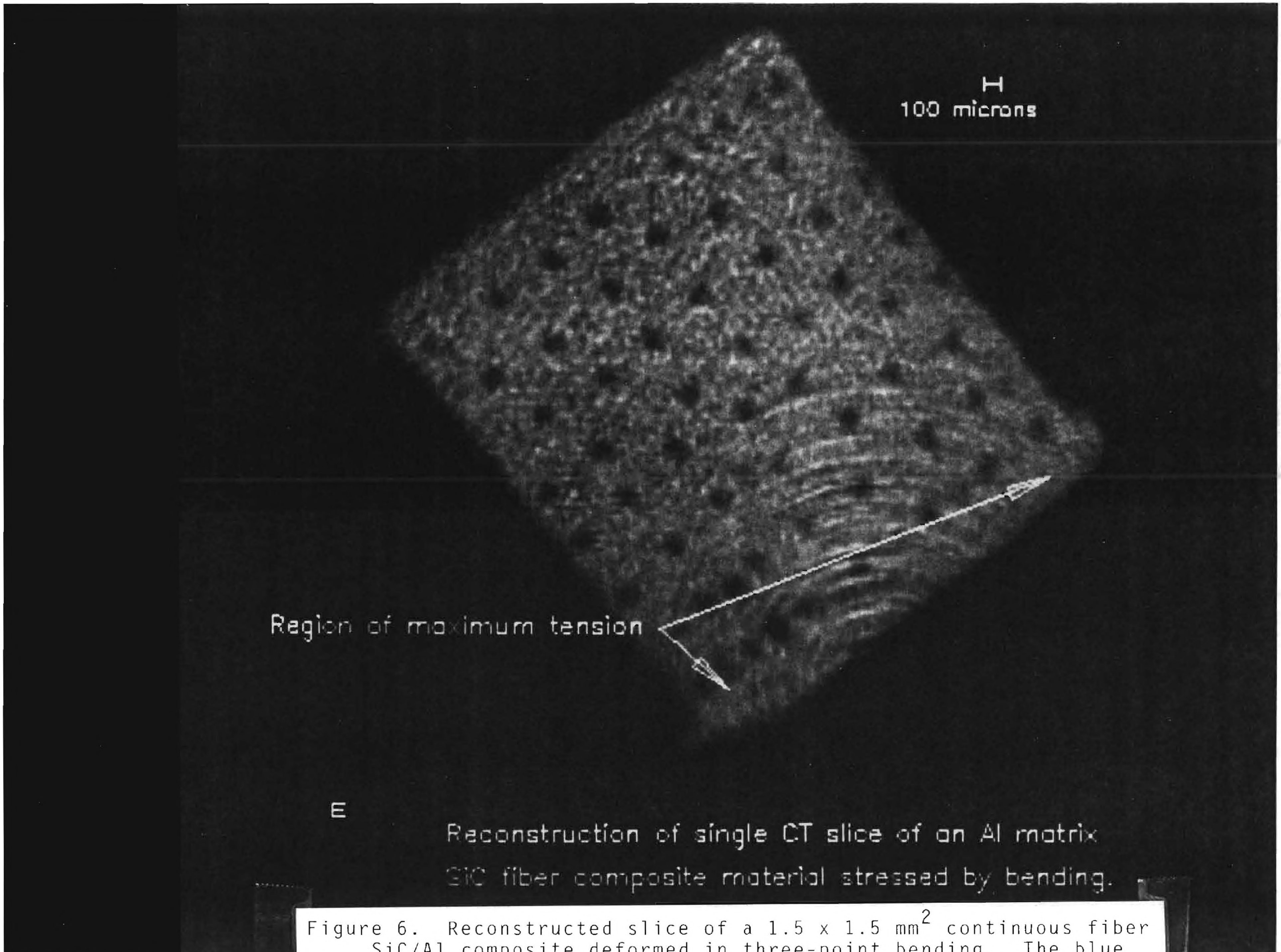

Figure 6. Reconstructed slice of a 1.5 x 1.5 mm^2 continuous fiber SiC/Al composite deformed in three-point bending. The blue circular images are the fibers' carbon cores. At one fiber's position the red image indicates a crack.

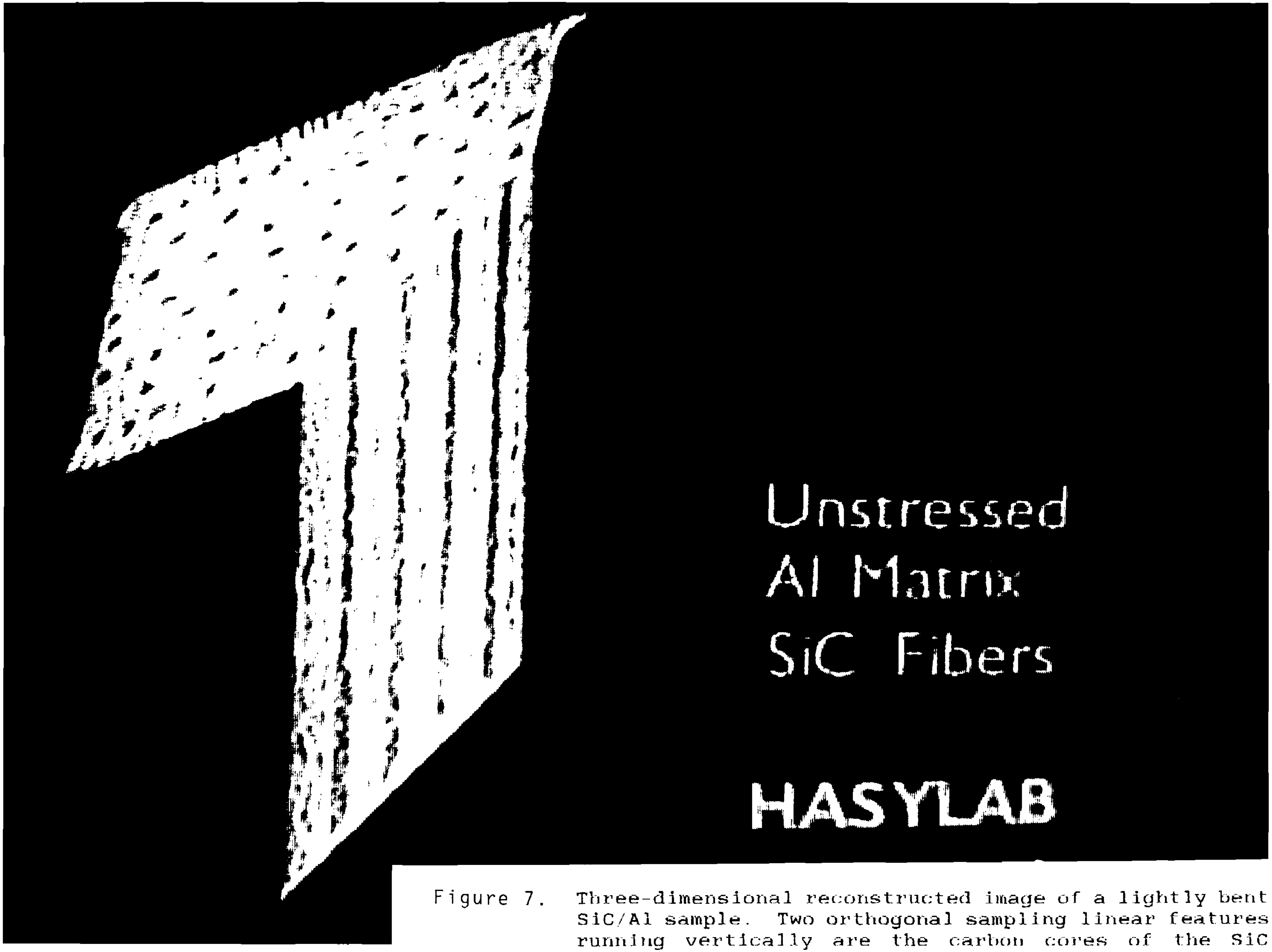

Figure 7. Three-dimensional reconstructed image of a lightly bent SiC/Al sample. Two orthogonal sampling linear features running vertically are the carbon cores of the SiC fiber.

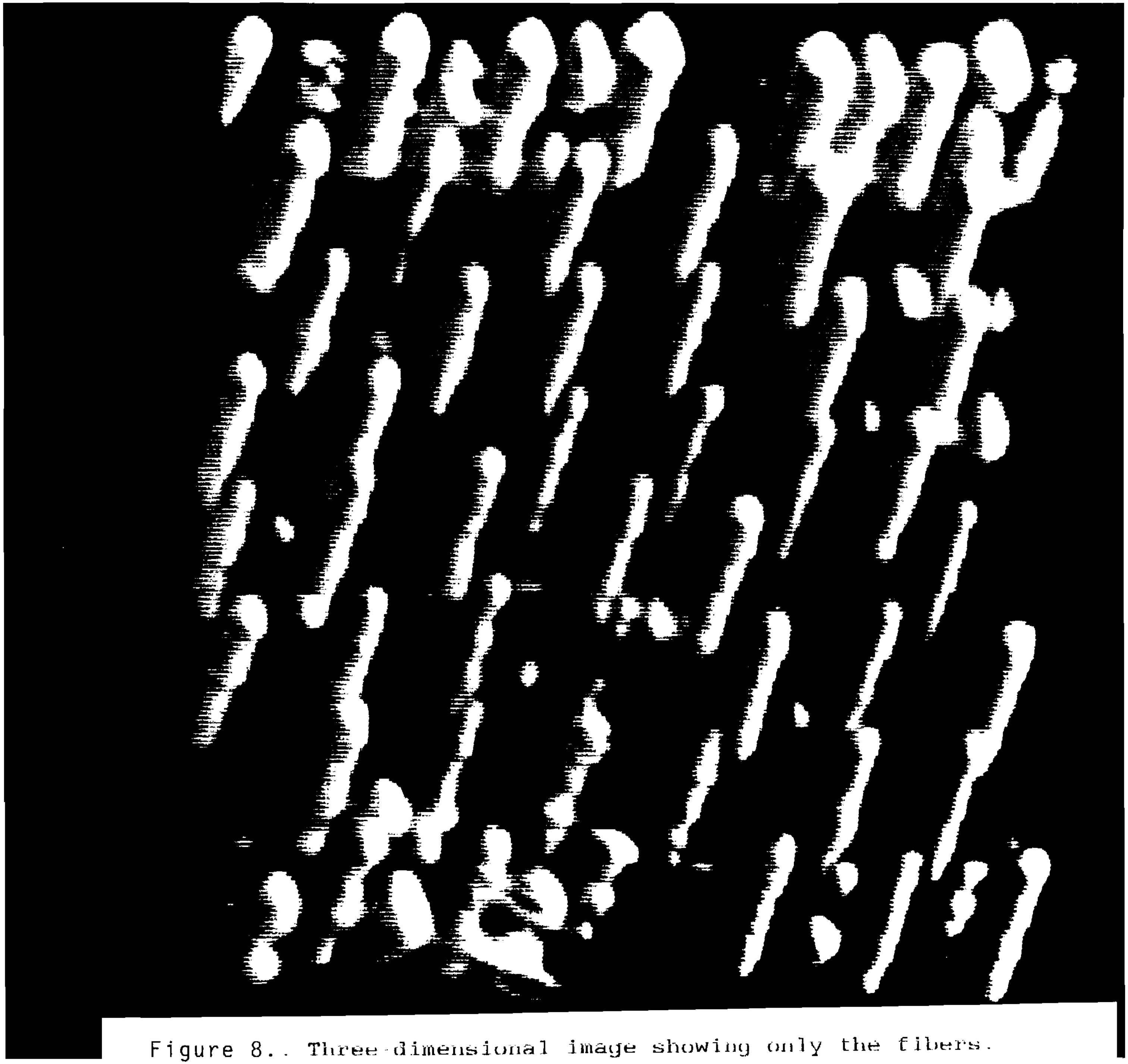

Figure 8.. Three-dimensional image showing only the fibers.